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ANALYSIS OF FLUID/MECHANICAL SYSTEMS USING EASY5

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SUMMARY

This paper illustrates how the use of a general analysis package can simplify modeling and analyzing fluid/mechanical systems. One such package is EASY5, a Boeing Computer Services product. The basic transmission line equations for modeling piped fluid systems are presented, as well as methods of incorporating these equations into the EASY5 environment. The paper describes how this analysis tool has been used to model several fluid subsystems of the Space Shuttle Orbiter.

INTRODUCTION

Modeling complex fluid/mechanical systems can involve difficulties beyond describing the system numerically. Not only does the task involve coding of the actual equations, the analyst is also faced with numerical integration of those equations, discretization of the system, and post-processing of the results. Thus, there exists a need for a tool which combines these processes into a single package. Boeing Computer Services EASY5 analysis program has been found to be one such tool which can be used to effectively model fluid/mechanical systems. With the advent of fast workstations based on RISC chips, graphically interfaced analysis programs for system analysis are highly efficient.

Modeling using EASY5 can be done in a finite-element type manner using modular subroutines. The user defines the behavior of a single element within the system (such as pipe flow or a spring-mass system) using the appropriate user-supplied equations and then discretizes the system as a combination of these elements, similar to other finite-element method routines. The features of this code benefit the user by providing nonlinear and linear analysis capability. Nonlinear time-domain simulations can be run using one of several different integration methods. This package also has the ability to linearize the system to provide transfer function, root locus, eigenvalue, as well as other types of analysis. Also contained within EASY5 is a plotting routine which can provide plots of results for the different types of analysis.

While any of the systems that could be modeled using EASY5 could also be modeled using FORTRAN, this type of software represents a convenient combination of many of

the tools which the analyst requires and significantly reduces time required to develop a new system simulation.

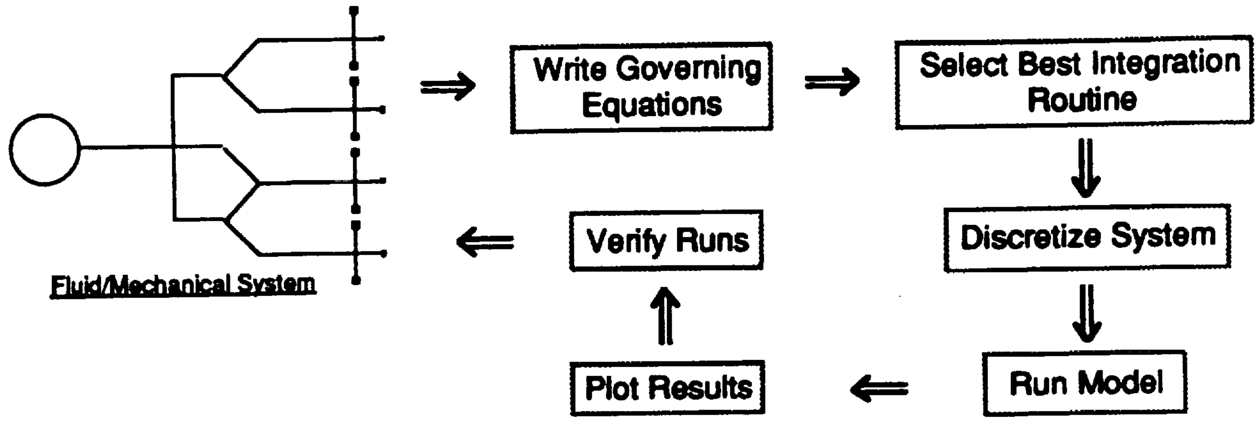


Figure 1. Flow chart of EASY5 modeling process.

THEORY

Most fluid/mechanical systems can be classified into subsets of similar components: pipe flow, pipe intersections (tees and crosses), orifices, volumes, and spring-mass systems. If the modeler has subroutines defining these components, they can be combined to represent complicated systems.

The basic building blocks for the fluid flow subroutines, or macros in EASY5 terminology, are the transmission line equations (ref. 1). The equations are listed below (see Figure 2 for notation).

$$I_i \ddot{m}_i = P_i - P_{i+1} - R_{fi} |\dot{m}_i| \dot{m}_i \qquad (1)$$

$$C_i \dot{P}_i = \dot{m}_{i-1} - \dot{m}_i ; \qquad i = 1, N \qquad (2)$$

where:

I_i = inertance of the i^{th} fluid element,

C_i = capacitance of the i^{th} fluid element,

$\dot{m}_i$ = mass flow into the i+1 element,

P_i = pressure at the center of the i^{th} fluid element

R_{fi} = resistance,

N = total number of fluid elements used to model a line segment

For a uniform line modeled with equal-length elements, the inertance, capacitance, flow resistance and temperature equations are the same for all elements and are given by (assuming one-dimensional flow and isentropic behavior):

$$I = \frac{L}{A} \qquad (3)$$

$$C = \frac{V}{\gamma RT} \tag{4}$$

$$R_f = \frac{RT}{2A^2P} f\left(\frac{L + L_e}{D}\right) \tag{5}$$

$$T = T_o\left(\frac{P}{P_o}\right)^{\frac{\gamma - 1}{\gamma}} \tag{6}$$

where:

L = fluid element length
A = flow area
γ = polytropic process exponent
T = temperature
R = gas constant
f = friction factor (pipe flow)
D = line internal diameter
L_e = equivalent length for minor losses

Equations 3, 4, and 5 specify the flow parameters for gas systems. These parameters can also be expressed for a liquid system by using the bulk modulus and density of the fluid.

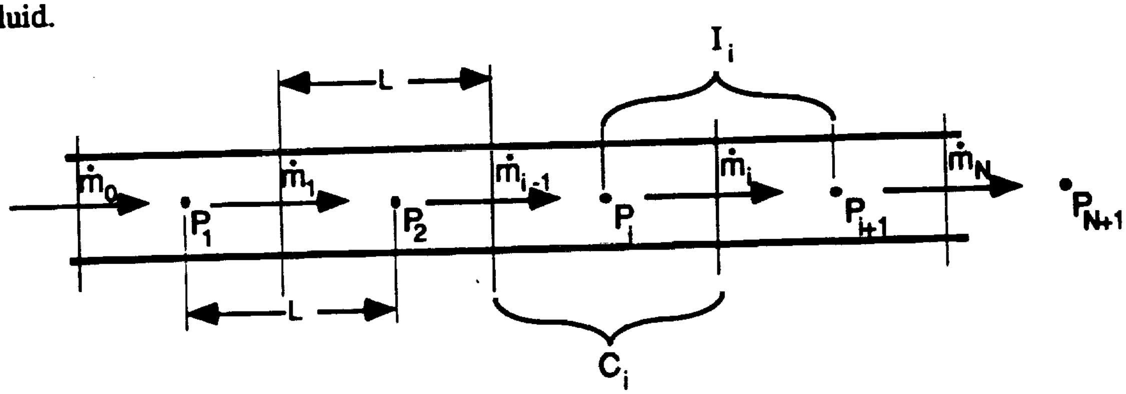


Figure 2. Typical discretization of a fluid line segment

The standard transmission line equations can be modified to handle flow through tees and crosses by using additional flow equations. Volumes of changing size can be modeled using Equation 7, which assumes an isentropic process.

$$\dot{P} = \gamma(\dot{m}RT - P\dot{V})/V \tag{7}$$

The mass flow rate through an orifice is given by the familiar relationship (ref. 2)

$$\dot{m} = C_D A \sqrt{\frac{2\gamma}{(\gamma-1)R}\frac{P_2}{\sqrt{T_2}}}\sqrt{\left(\frac{P_1}{P_2}\right)^{\frac{2}{\gamma}} - \left(\frac{P_1}{P_2}\right)^{\frac{\gamma+1}{\gamma}}} \tag{8}$$

where C_D = orifice discharge coefficient, A = orifice area, and the subscripts 1 and 2 denote pressure/temperature upstream and downstream, respectively. A valve can be modeled using a variable area orifice. To approximate the opening of the valve, it has been found that varying the area using a hyperbolic tangent function yields the best results. However, any type of continuous or discrete function could be used as long as the rates of change within the model do not become too large for the integration step size.

Because EASY5 requires systems of first order differential equations, spring-mass systems are modeled by breaking the system's second order differential equations into first order equations. For example, the governing differential equation for a spring-mass-damper system,

$$\ddot{x} = -(c\dot{x} + kx - F(t))/m \tag{9}$$

may be replaced by the following two first-order equations:

$$\dot{v} = -(cv + kx - F(t))/m \tag{10}$$

$$\dot{x} = v \tag{11}$$

APPLICATION

An EASY5 macro is very similar to a FORTRAN subroutine. The macro contains the code required to describe the behavior of a single model element, e.g., a transmission line element, spring-mass combination, etc. The parameters which define the physical characteristics of the element are inputs to the macro, as are the boundary conditions for that element as calculated by an adjacent element. The outputs of the macro are the values calculated using the code within the macro and the specified inputs. A model is then built by linking a series of macros together using their inputs and outputs.

For example, consider the three element section of a model shown in Figure 3. An acoustic line is being modeled using a macro named 'TR' (EASY5 macro names consist of 2 characters). The acoustic line macro is a combination of the pressure/flow differential equations, isentropic temperature relationship, and a curve fit of the Moody diagram. The macro first calculates the current temperature assuming an isentropic process. Next, the macro uses a logic block to determine which way flow is moving. After the flow direction is determined, the friction factor is calculated using the Reynold's Number and the equations describing the Moody diagram. The flow and pressure derivatives are then calculated and integrated. These outputs are then used as inputs to other elements.

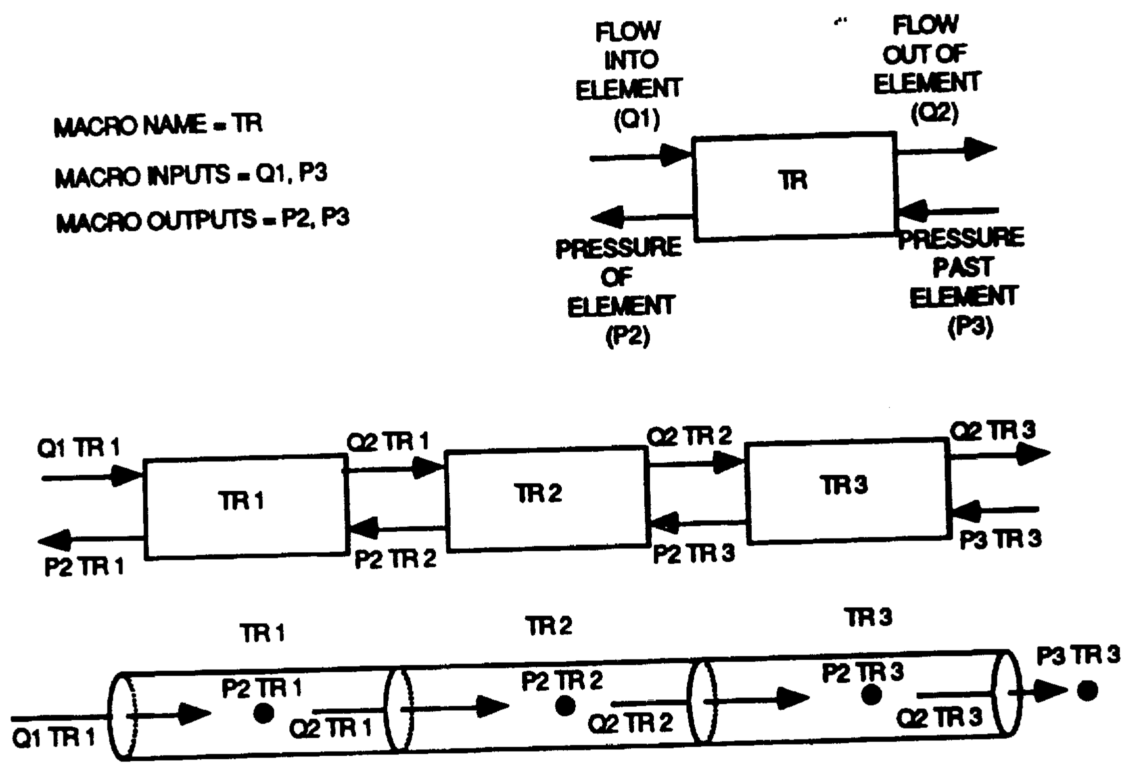


Figure 3. Acoustic Line Connection and a Simple Three Element Model

When modeling an acoustic line, the line is broken up into a series of elements. The length of each element is based on the highest frequency of interest and the length of the line. The usual FEM rules regarding the minimum and maximum number of elements in a line apply to this type of modeling. An acoustic line macro is used for each element. The pressure derivative is based on the flow out of the previous element and the flow out of the current element. The flow derivative is based on the pressure of the current line element and that of the next line element. Therefore, the flow of the previous element and the pressure of the next line element must be inputs to the current line element.

A long length of line can require an excessive number of transmission line elements. In order to minimize the effort required to build the model, a multiple element transmission line macro was developed. The code internal to the macro is set up in an array format. The user specifies the number of sub-elements to be contained within the element, ranging from 1 to 999. This development greatly reduces the amount of time required to develop a model of a system.

The time step used for nonlinear time-domain simulations varies depending on the nature of the model. The optimum time step is found through an iterative process for fixed time step integrators, while variable time step integration schemes have logic for adjusting integration time step to maintain solution accuracy with the largest acceptable time step. Too large of a time step results in numerical error due to large rates of change. Too small of a time step can cause excess round-off error. The optimum time step for fixed step solutions has been found to be one which, when reduced, gives results identical to those of the previous step size. The recurrence formula for the wave equations must be considered when choosing a time step size. Therefore, the following relationship needs to be considered,

$$\frac{1}{c} \le \frac{\Delta t}{\Delta x} \tag{12}$$

where Δt is the time step size, Δx is the element length and c is the speed of sound of the media being modeled. A detailed explanation can be found in reference 3.

EASY5 offers several different types of integration algorithms. These include:

Fixed-Step	Variable Step
Euler (1st order)	BCS Gear
Huen (2nd order)	Adams-Moulton
Fixed-Step Runge-Kutta (4th order)	Stiff Gear
	Variable-Step Runge-Kutta

The variable step integration schemes adjust the integration step size based on how fast the system states are changing. Ideally, these methods would be desirable for use since they represent a potential execution time savings. However, it has been the authors' experience that the variable step methods are not particularly compatible with the macros that have been developed to model fluid systems, due to the quadratic damping term and the large pressure derivatives associated with small elements. Typically, the integrator ends up iterating excessively trying to optimize the step-size, thereby greatly increasing the execution time. Good results have been obtained using the variable-step methods on spring-mass systems.

Another nonlinear analysis feature of EASY5 is steady state analysis. The steady state command returns the equilibrium operating condition of the model. The model rates of change are essentially zero for this analysis.

EASY5 is also capable of linear dynamics analysis. This is done by linearizing the state equations in the model by perturbating them about the operating point to create a linear perturbation model. This linear model can then be used for other types of analysis such as transfer function, root locus, closed loop eigenvalue and other frequency domain analyses.

EXAMPLE 1 - 750 PSIA MPS HELIUM SUPPLY REGULATOR

Background

In this example the authors were asked to investigate a problem with the Space Shuttle main propulsion system (MPS) 750-psia helium pressure regulator. Two regulators experienced full-open failures due to high frequency (900 Hz), high amplitude oscillations. The failures took place on a new test stand which was constructed to replace the original regulator qualification stand after it was destroyed in the collapse of the building in which it was located.

The authors were tasked to develop dynamic models of the test stand as well as models of all three MPS engine helium supply system configurations utilizing an existing model of the regulator developed by the vendor. The purpose of the models was to determine the source of the oscillations, evaluate potential for oscillations on the Orbiter, and to test possible solutions for correcting the problem.

Modeling Effort

The EASY5 software was selected for this modeling effort. It was not possible to directly convert the vendor's regulator model into EASY5. Therefore, the model had to be created with EASY5 macros using the existing model as a guide. EASY5 macros of the components discussed in the Theory section of this paper were assembled to represent the actual regulator (see Figure 4 for regulator schematic). The model consisted of one spring-mass macro (containing 21 degrees of freedom), twelve flow (tube, annular and orifice) macros, and nine volume macros. The spring-mass macro contained the necessary equations to model the movement of the poppet, valves and metal bellows. The hard stops in the regulator were modeled by using bi-linear springs.

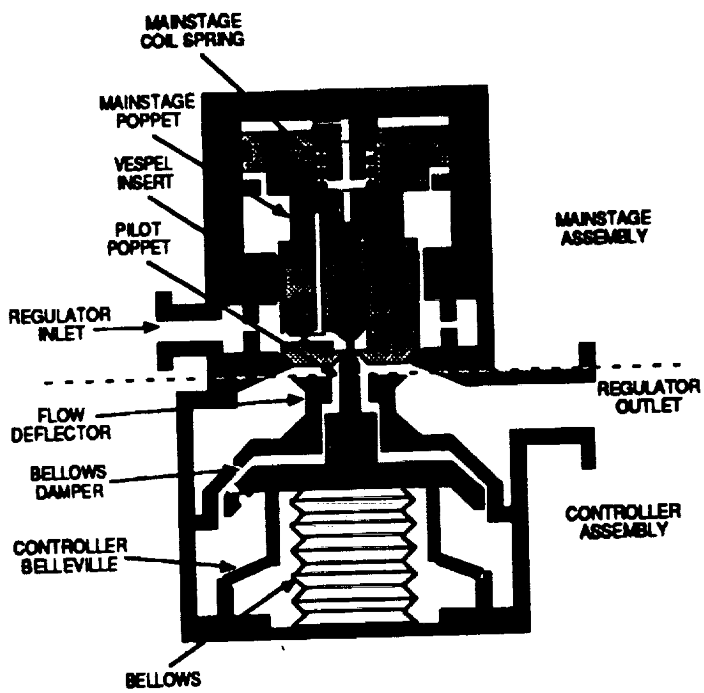


Figure 4. MPS helium supply regulator schematic

Analysis

Using the transfer function option of EASY5, it was determined that there was a 180 degree phase shift between the pressure sensed and actual pressure of the regulator's exit at the frequency range that the oscillations occurred. The shift would cause the regulator to reinforce any pressure oscillations occurring downstream of the regulator in this frequency range.

A model of the complete newly constructed verification test stand was developed. The oscillatory behavior of the regulator was duplicated using the time simulation option and it matched the first acoustic mode downstream of the regulator. The new test stand line configuration's fundamental frequency coincidentally matched that of the regulator's bellows, which lead to fatigue failure of the bellows. Models of the complete Orbiter MPS helium supply system were also constructed (Figure 5). Each engine supply system consisted of approximately 1000 degees-of-freedom.

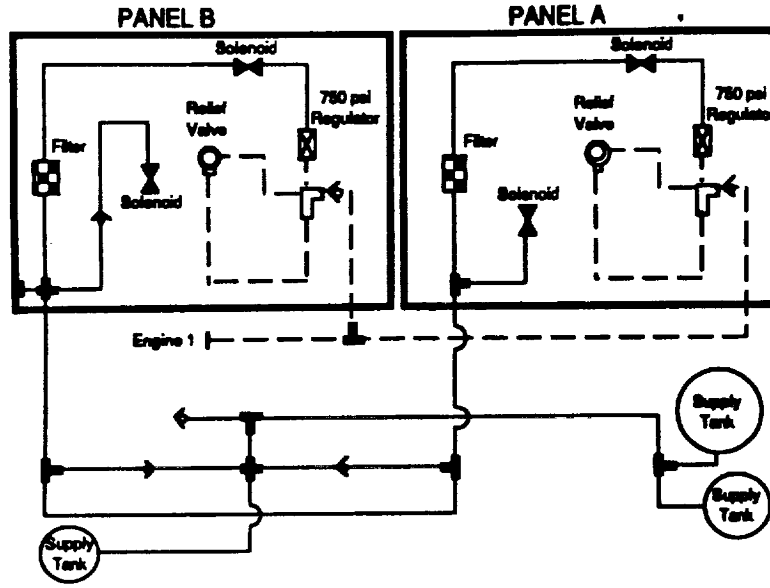


Figure 5. Diagram of Engine 1 helium supply system

The EASY5 model of the regulator was used to guide and evaluate design changes proposed by the vendor. The final design showed stable operation in both tests of actual hardware and in numerical time simulations with the math model. Figures 6 and 7 show a Bode plot and simulation results of the regulator before and after the redesign.

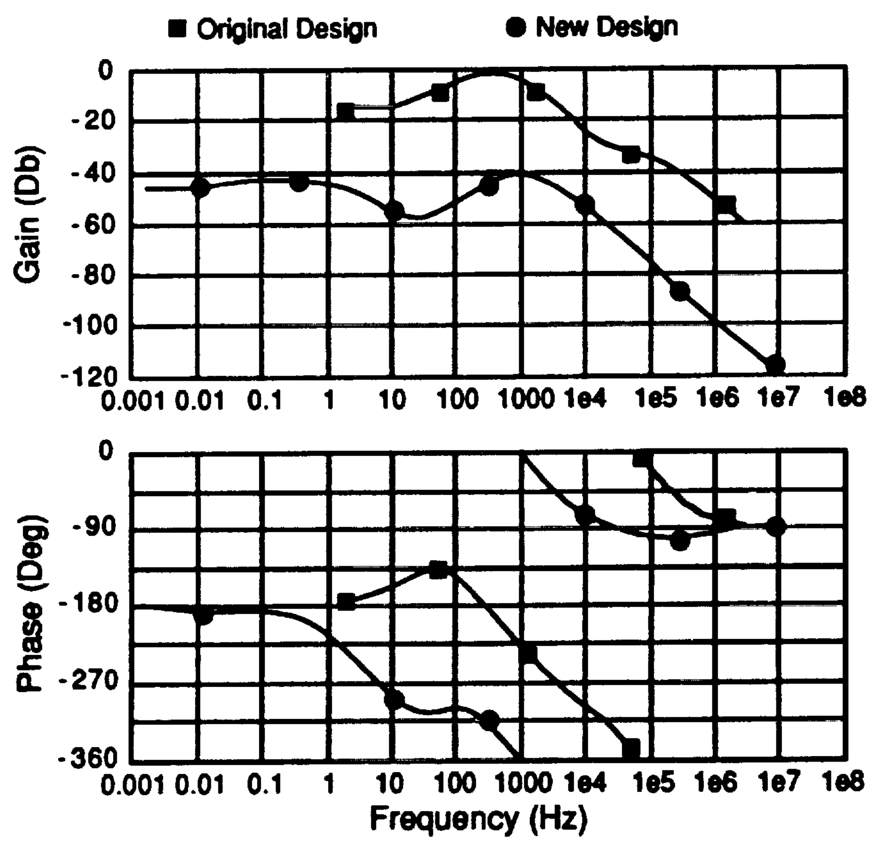
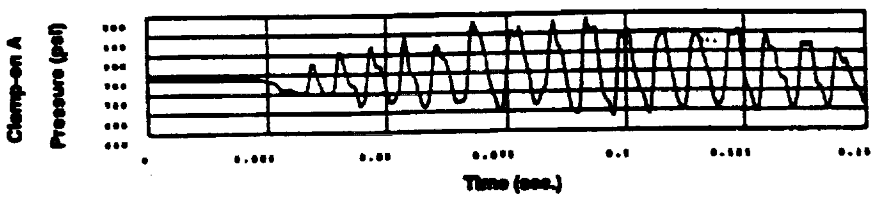
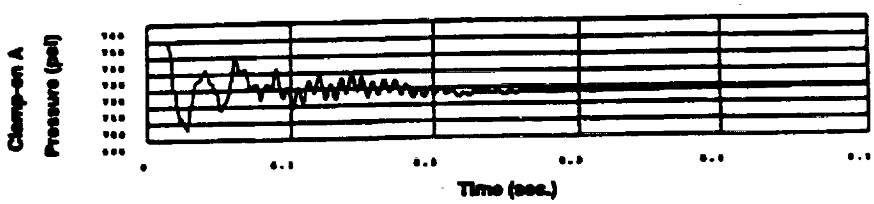


Figure 6. Bode plot of regulator outlet pressure to controller pressure transfer function.



Regulator Pressure Prior to Redesign



Regulator Pressure After Redesign

Figure 7. Time simulations of the regulator before and after redesign.

EXAMPLE 2 - PRCS THRUSTER

This second example describes the use of the EASY5 software in developing propellant feedline dynamic models of the Orbiter's Primary Reaction Control System (PRCS) thruster test stands. Over the course of the modeling project, the models evolved from a simple waterhammer analysis to a complex two-phase flow analysis of the chug stability of the thruster.

Background

Combustion stability testing of the PRCS thruster involves injecting helium into the propellant feedlines in order to provide a combustion disturbance. The injection rate is not a precisely known quantity. The test stand is designed to produce a nominal flow of helium during steady state conditions. However, due to ignition and shutdown transients, the flow of helium into the thruster can vary widely over time. For this reason an analytical model was desired to predict the amount of helium ingested by the thruster. The propellants for the thruster are monomethylhydrazine and nitrogen tetroxide, both of which are liquids at the operating pressure and temperature.

Modeling

The test stand models were developed using macros similar to those used for the MPS helium regulator project. The models are comprised of single- and two-phase elements. Line elements several inches upstream of the helium injection point are capable of two-phase flow representation, while the remainder of the transmission line elements are single-

phase (see Figure 8). The two-phase macros assume a homogeneous gas-liquid mixture, ideal and isentropic behavior of the gas phase, and are based on equation (13):

$$\dot{P} = \frac{\gamma R T \dot{m}_g + \frac{\gamma \dot{m}_l P}{\rho_l}}{V_g + \frac{\gamma V_l P}{B}} \tag{13}$$

where

B = liquid bulk modulus

V_g = gas volume of element

$\dot{m}_g$ = mass flow of gas

$\dot{m}_l$ = mass flow of liquid

ρ_l = density of liquid

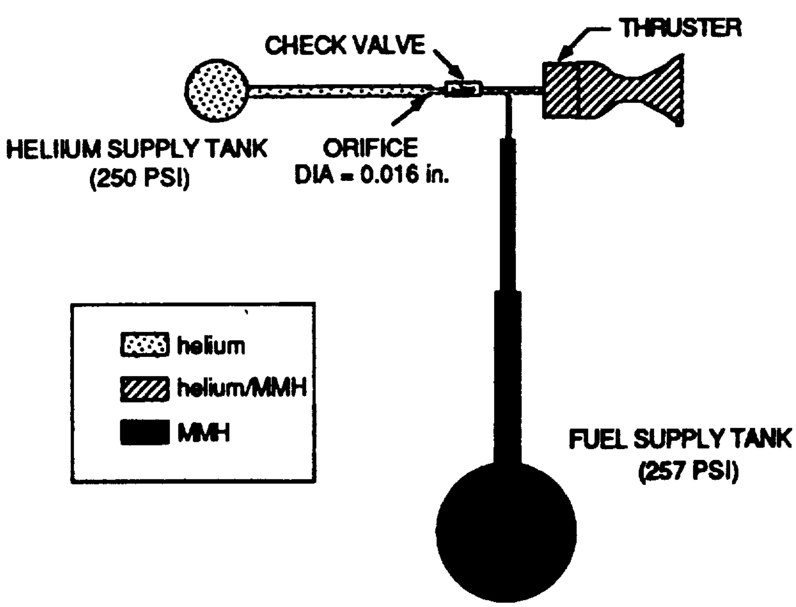


Figure 8. Schematic of PRCS Test Stand Model

Initial simulations used a time history table of thruster chamber pressure measured in test firings as the boundary condition at the end of the propellant feedline. Based on the steady state flow rate and pressure drop, the resistance of the line could be fine-tuned to achieve the required flow parameters. Time-domain simulations used fourth-order Runge-Kutta as the integration method, with an integration step size of 1.0E-05 seconds.

Results from these models were in the form of time history plots of system parameters. Sample results are shown in Figures 9 and 10. Figure 9 illustrates the behavior of fuel feedline pressure just upstream of the thruster. Information from these simulations was also used to size the test stand feedline lengths to obtain a waterhammer frequency similar to the actual vehicle installation. Figure 10 shows the helium ingestion time history for a single 160 millisecond firing. Simulations can be executed sequentially such that the ending conditions for one simulation are the initial conditions for the next. For the PRCS modeling task, this allowed a sequence of firings to be simulated so that the amount of helium residing in the lines would build as the test firing sequence progressed.

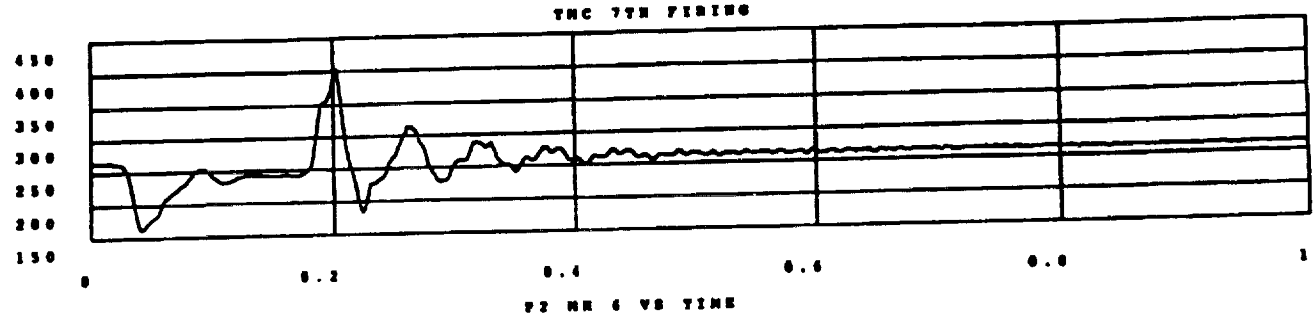


Figure 9. Typical simulation result.

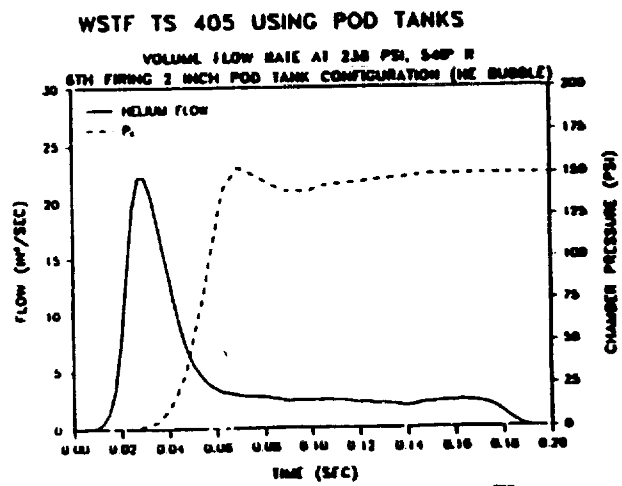


Figure 10. Helium injection profile.

Evolution of the PRCS Models

The PRCS modeling effort expanded beyond the scope of the initial test stand models. In order to understand the mechanism behind the low frequency (600-1000 Hz) chug mode of the thruster, a more detailed model of the thruster valves, manifolds, and injectors was developed. The valve model is similar in concept to the fluid/mechanical model developed for the MPS regulator task. Variable area orifices were used to represent the opening and closing of valve passages as the valve poppet moved. The stiffness of the poppet spring is represented by tabular data taken from tests conducted during the valve development program. Leak rates around the poppet seals are simulated by not allowing the variable area orifices to close completely.

A diagram of the model schematic is shown in Figure 11. Test stand vibration, which may contribute to some of the high amplitude pressure and acceleration oscillations

observed during tests, is included in the model. The test stand is treated as a single degree-of-freedom system having mass, stiffness, and damping characteristics close to that of the stand. Test stand motion is applied to the fluid system through macros which have moving boundaries. The test stand velocity is applied to these elements as an element wall velocity, which drives the element pressure derivative. Also included in the model is the combustion timelag. The flow out of the last injector element is delayed from combusting (expanding into gas) by a specified amount of time. This is accomplished through an EASY5 continuous delay macro. The chamber pressure is calculated based on the capacitance of the chamber, the amount of fuel and oxidizer flowing into the chamber, and the amount of gas flowing out of the chamber. The amount of gas flowing out of the chamber is determined using the characteristic velocity (c^*).

Due to the small size of the injector, very small elements were necessary to obtain the required fidelity. The size of these elements dictated that the integration step size also be small. The optimum step size was found to be 1E-07 seconds, using fourth-order Runge-Kutta as the integration method.

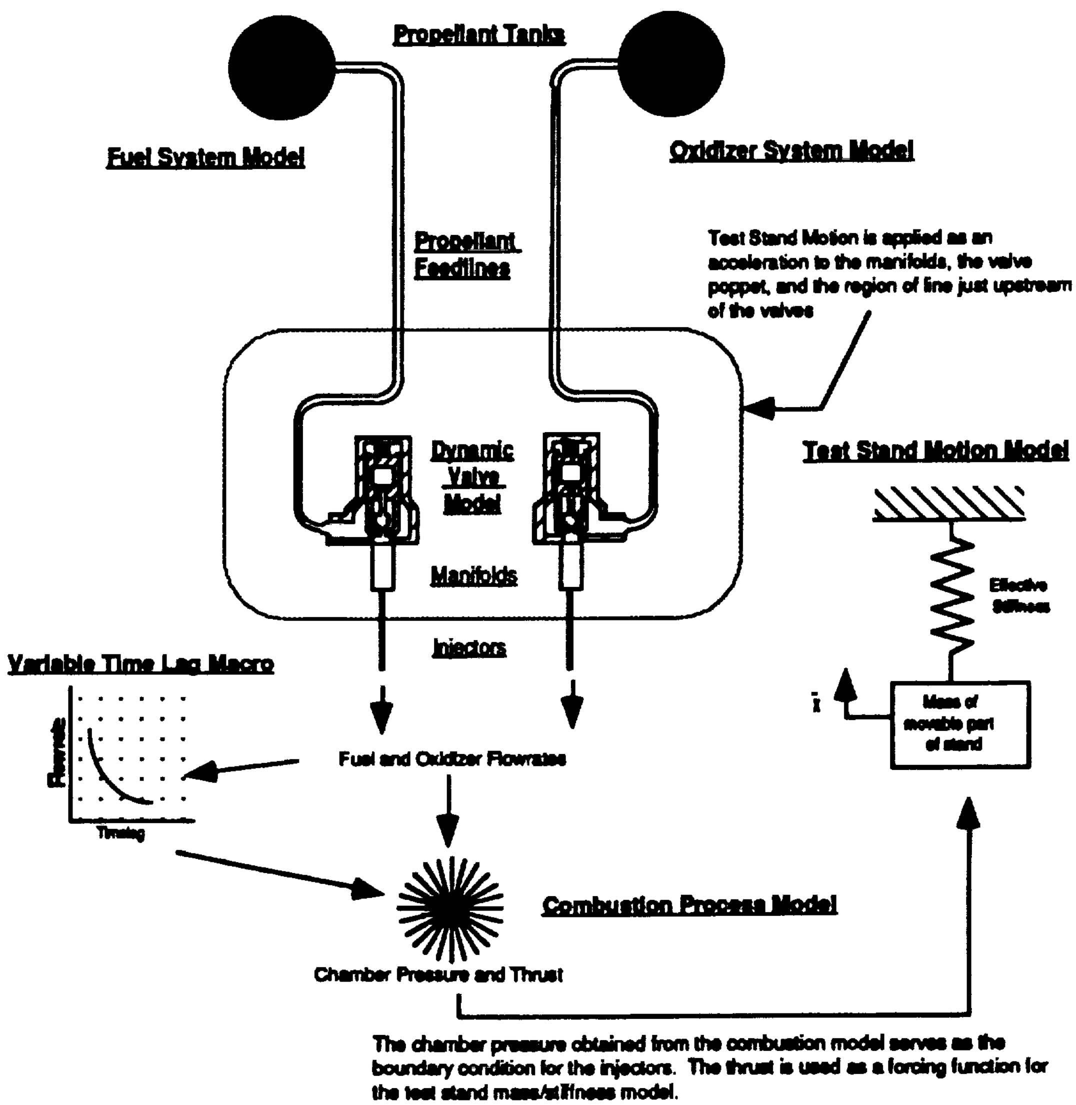


Figure 11. Schematic of detailed PRCS thruster model.

CONCLUSIONS

The use of a general analysis package for fluid/mechanical system modeling has been demonstrated. The general transmission line equations and numerical approximations of other fluid system components have been successfully integrated into the EASY5 analysis program. The combination of integration routines, graphics capability, and pre- and post-processor has proven to be effective and convenient for modeling these types of systems. High fidelity models of several complex non-linear fluid, structural, and mechanical system interactions were developed which correlated well with test data and provided a basis for analyzing and eliminating causes of adverse dynamic interactions.

NASA-JSC Propulsion Branch is continuing to use EASY5 for other propulsion systems. A substantial set of macros and models have been developed which allow quick and accurate analytical results to be obtained for a wide variety of propulsion fluid and mechanical systems.

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